

## Verbal Memory Span in Children: Speech Timing Clues to the Mechanisms Underlying Age and Word Length Effects

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According to the prevalent articulatory loop hypothesis of memory span (Baddeley, 1986), subjects recall items from a decaying phonological store that is refreshed by a covert articulatory process. The rate of covert articulation is said to determine memory span. The present research indicates that this account underemphasizes effects of (1) other covert mnemonic processes and (2) overt pronunciation in recall. Memory span and maximal speech rate for sets of one-, two-, and three-syllable words were examined in groups of children with mean ages of 4;5 and 8;8. Although the usual linear relation between the maximal speech rate and memory span was replicated, speech timing measurements based on the memory responses revealed that age and word length effects had different effects on the timing of responding. Whereas word length affected the duration of words in the response but not silent intervals, age affected the duration of silent, preparatory and interword intervals in the response but not the duration of words. These results are discussed in light of the hypothesis that the speeds of multiple, mnemonically relevant covert and overt processes affect memory span. © 1994 Academic Press, Inc.

Verbal memory span, the largest number of words that can be repeated in correct serial order, is time-limited in an interesting way. A linear relationship is obtained between a subject's memory span for a particular set of items and the maximal rate at which the subject can pronounce those items (Baddeley, Thomson, & Buchanan, 1975; Case, Kurland, & Goldberg, 1982;

Cowan, Day, Saults, Keller, Johnson, & Flores, 1992; Hulme, Thomson, Muir, & Lawrence, 1984; Naveh-Benjamin & Ayres, 1986; Nicolson, 1981; Schweickert & Boruff, 1986; Standing, Bond, Smith, & Isely, 1980; Zhang & Simon, 1985). In some of these studies, maximal speaking rate was manipulated by varying the spoken length of the stimulus words, whereas some of them focused on individual differences or age differences in speaking rate. More detail is needed before the causal mechanisms behind the relation between speech rate and memory span in these situations can be understood.

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The dominant account of the relation between speech rate and memory span is the "articulatory loop" theory put forward by Baddeley (1986). It includes the same explanation for the effects of variations in speech rate due to stimulus variables and to subject variables. According to this ac-

count, a transient, phonological memory representation is used to retain verbal items for short-term recall. This memory trace is presumed to decay within about 2 s unless it is refreshed through a rehearsal (covert articulation) process. The theory attributes effects of stimulus materials and of individual differences on memory span to their influences on the speed of articulation. The main assumption is that the more quickly the subject can articulate the items, the more items can be refreshed in memory before they decay beyond a critical point. It is further assumed that, once an item has decayed from the phonological store, there is no possibility of refreshing it through rehearsal and no other source of recall.

There are important questions about mechanism that remain unresolved, however, within the articulation loop framework. First, the limit in recall could occur because of limitations in the rate of covert articulation, the rate of overt pronunciation during the recall period, or both. If the limit is one of covert articulation (as Baddeley, 1986 tended to assume), it presumably occurs because items decay from phonological storage if they are not refreshed often enough. If the limit is overt pronunciation, it presumably occurs for the similar reason that items decay from storage during the recall period if they are not pronounced soon enough. As a possible modification of the articulation loop hypothesis, the speed of other mnemonically relevant covert processes also could play a role in memory span.

In search of support for the hypothesis that overt output plays a role, Cowan et al. (1992) manipulated independently the length of words in the first and second halves of each list to be recalled and also manipulated the order of recall (which could be forward or backward). It was found that the effect of word length occurred primarily in the lengths of whichever words were to be repeated first. The account offered by Cowan et al. was that the words to be repeated first delay the overt

repetition of the remaining words in the list, whereas the words to be repeated last do not delay anything else and therefore have much less effect on recall.

Other research indicates that word length has at least two effects on verbal memory span. It affects the rate of overt pronunciation in subjects of any age, and it affects the rate of covert rehearsal in older children and adults. Baddeley, Lewis, and Vallar (1984) found that the word length for auditory lists could be abolished by suppressing covert articulation, but only if the articulatory suppression task was continued through the response period (using a written response). This continued suppression could be needed to eliminate overt output effects. Henry (1991a) found no effect of word length in 5-year-olds when a pointing response was used instead of a verbal response, suggesting that the output delay effect might account for all of the word length effect in these young children. A word length effect still was obtained with a pointing response in 7-year-olds, which may reflect an involvement of rehearsal as well as overt pronunciation by that age.

It cannot be taken for granted that the effects of subject variables on recall occur through the same mechanisms as have been found for the stimulus variable of word length. An example of how they could differ is that word length could influence primarily the overt pronunciation rate, whereas subject variables instead might influence the rate of some covert process or processes.

The results of Cowan (1992) suggest that the above example may be more than just hypothetical. This study focused on a memory span task for monosyllabic words in 4-year-old children. Unlike previous studies of memory span, a waveform editor was used to measure the latency of onset and the duration of each child's spoken recall. The main purpose was to distinguish between two different hypotheses about what occurs during the response period. According to the first hypothesis, phonological

memory decays steadily during this period. From that hypothesis, one would expect that spoken recall could not last longer than about 2 s, the presumed duration of phonological memory (Baddeley, 1986). According to an alternative hypothesis, though, there are covert processes taking place during the silent intervals between words in the spoken response that can serve to reactivate items in phonological memory. Because it was found that the duration of responses depended on the subject's span and lasted up to about 5 s in the more proficient subjects, it was argued that the second, decay-and-reactivation hypothesis is to be preferred.

Cowan (1992) also obtained a more detailed view of the timing of spoken recall. The mean duration of the preparatory interval between the stimulus list and response, and the duration of each word and each interword pause in the response, were measured separately. The results indicated that, for span-length lists, neither the durations of words in spoken recall nor the durations of silent intervals between words changed as a function of the subject's span. However, the durations of interword pauses in the response did depend on the list length. Averaged across subjects, pauses were shorter within lists that were one below the subject's span (which we will term "span - 1 length" lists) than for span-length lists, and were even shorter in lists that were two below span ("span - 2 length" lists). No such effect of list length on the duration of words in the response was obtained.

The exact basis of the effect of list length on interword pauses is uncertain. However, as Cowan (1992) noted, a similar effect was obtained by Sternberg, Wright, Knoll, and Monsell (1980) in an experiment with adult subjects who were to repeat short lists as quickly as possible following a ready signal. Sternberg et al. accounted for their results on the basis of a hypothesis (proposed originally by Sternberg, Monsell, Knoll, & Wright, 1978) that subjects must

mentally scan through the list of words during each silent interval in order to identify the correct item to be spoken next. Of course, others would suggest that the same sort of relation might obtain if subjects actually search through the list in a capacity-limited, parallel manner (e.g., Ratcliff, 1978) instead of scanning items serially. The point that is relevant here is that the time needed to search for a particular list item would be affected by the number of items in the list, and the interword pause durations would depend upon that search time.

Cowan (1992) found that interword pauses in span-length lists were the same for 4-year-old children independent of span, but that pauses were shorter in sub-span lists. If it can be assumed that pauses in the response are used for memory search operations, then these results imply that the more capable children were able to search through more items than the less capable children in the same amount of time. It was proposed, therefore, that children's rates of memory search differ and are related to their memory spans.

Support for a relation between search rate and memory span has been obtained in a previous literature review (Cavanagh, 1972), but the factor examined was the type of stimuli used (letters, words, syllables, etc.) rather than individual differences in search rate. In an individual-subject analysis, Brown and Kirsner (1980) found that the linear relation between search rate and memory span for different materials held in some adult subjects but not others, and that search rate was not an important variable distinguishing among subjects. However, search rate might be a more important factor in discriminating among young children (Cowan, 1992) and among age groups in childhood.

The discussion of Cowan (1992) included some predictions about the effects of word length and age on the timing of spoken recall. The predictions were based partly on the assumption that the silent intervals be-

tween words in spoken recall are used to carry out memory search processes. It has been found previously that the rate of memory search is not affected by word length (Clifton & Tash, 1973), no matter whether it is item or sequential information that is searched for (Chase, 1977), in contrast to the large effect of word length on rehearsal rate (Baddeley et al., 1975). Accordingly, no effect of word length on the duration of silent intervals in the responses was predicted. It was expected that word length would affect the duration only of spoken words in the response.

Cowan (1992) found that, when subjects of different memory abilities were compared on lists of fixed lengths that were repeated correctly, interword pauses were shorter in the more able subjects. These results are consistent with the hypothesis that subject differences in recall may be related to differences in the speed of covert mnemonic processes but not to differences in overt pronunciation rates, in distinct contrast to word length differences.

It is possible that age differences would operate in a manner analogous to subject differences within 4-year-olds. Let us suppose that one effect of age relevant to memory span is a developmental increase in the speed of memory search (possibly through some changes in the exact nature of that search) and let us entertain the assumption that the speed of search determines the duration of silent intervals in the response. These assumptions lead to the prediction (Cowan, 1992) that there should be an effect of age on the silent intervals between words in the memory response because older children should carry out search processes more quickly than younger children. There is no expectation that the duration of words in the memory response necessarily would change with age, because the response is not speeded.

In the present study, the effects of word length and age differences on the timing of spoken recall were examined with children

of two ages in order to test the above predictions and thus explore the mechanisms underlying memory span and its development.

## METHOD

### *Subjects*

The subjects were children from the vicinity of York, England. They included a younger group of 16 children with a mean age of 4;5 ( $SD = 1.6$  months) and an older group of 23 children with a mean age of 8;8 ( $SD = 5.7$  months). The children had no known hearing or learning problems.

### *Stimuli and Procedure*

The stimuli included sets of short (monosyllabic), medium (bisyllabic), and long (trisyllabic) words matched across sets for frequency and conceptual class according to the norms of Carroll, Davies, and Richman (1971). The set of short words comprised *bath, belt, cake, doll, glove, leaf, pig, and spoon*; the set of medium words, *basket, candle, giraffe, hammer, kettle, pencil, scissors, and whistle*; and the set of long words, *aeroplane, banana, butterfly, elephant, kangaroo, piano, policeman, and umbrella*. ("Aeroplane" is the British counterpart to the American word "airplane.")

The data were collected in a single session of approximately 25 min. Recorded, digitized versions of the words were presented on an Apple Macintosh SE/30 computer through an external, amplified speaker, using the memory span program described by Cox, Hulme, and Brown (1992). Memory span measures were followed by speech rate measures. Within the memory span segment, spans were determined separately for the three word lengths, and the order of tests for the three lengths was varied across subjects.

*Memory span task.* Subjects were tested individually in a quiet room. Each list to be recalled consisted of words spoken at a rate of one item per second, and the task was to

repeat each list as soon as it ended, preserving the order of words. Within the span determination test at each word length, the list length (number of items) was held constant for four consecutive lists. For the younger children each test began with lists of two items. For the older children each test began with lists of three items but regressed to two items if the subject did not perfectly repeat the three-item lists. Following the four lists at a particular list length, the list length was increased by one item. When the subject made an error on either three or four of the lists at a given length, the test for that word length was terminated. The entire session was audiotaped. A lead from the stimulus output led to one channel of the recorder, and a microphone picked up the subject's response on the other channel.

*Speech rate task.* For each word length, the subject was presented with the eight words, in four pairs. The subject repeated each pair once for practice and then repeated the pair 10 times in a row as quickly as possible. The experimenter kept track of the number of repetitions so that the subject would not have to do so. The response time for this speeded repetition was recorded using a stopwatch, as in most previous studies of the relation between speech rate and memory span (e.g., Baddeley et al., 1975; Hulme et al., 1984; Naveh-Benjamin & Ayres, 1986; Schweickert & Boruff, 1986; Standing et al., 1980; Zhang & Simon, 1985). The order of word lengths and of words within each word length were varied across subjects.

*Timing measurements.* Recordings of the memory span sessions were examined in the same manner as Cowan (1992). Apple Macintosh Classic and SE computers equipped with the MacRecorder analog-to-digital converter and sound editing program (SoundEdit) were used to measure the time between the end of the stimulus list and the beginning of the child's spoken response, as well as the relative times of the beginning

and end of each word in the response. These measurements were made for all lists that were recalled correctly, but not for incorrectly recalled lists. The SoundEdit program allowed an oscillographic display of an entire trial at a time on the computer screen. A trained assistant used the mouse to select one spoken word at a time, listened to the selected segment through headphones, and adjusted the segment in this way until it exactly covered the word. The beginning and ending times of the selected word were recorded to the nearest 10 ms, and this process was repeated until the entire response was measured.

## DEPENDENT MEASURES

### *Memory Spans*

Spans for each word length were calculated according to two different methods. In the first measure, which we call the *maximal memory span*, each subject's span was taken to be the highest list length on which at least one trial was correct. This method was used primarily because we needed a whole-number span estimate in order to identify the list lengths to be used in memory response timing measurements. However, in order to obtain more precise measurements, an alternative method, which we call the *cumulative memory span*, also was used. It is calculated as the longest list length at which all four lists were repeated correctly, plus 0.25 for every subsequent list repeated correctly. For example, if a subject correctly repeated all four lists of length 4, three lists of length 5, and no longer lists, then the cumulative span would be 4.75 and the maximal span, 5. Cumulative span was modeled after Hulme, Maughan, and Brown (1991).

### *Speech Timing*

Speech timing measures came from both the memory trials and the separate, speeded pronunciation task. Most of the

analyses involving speech timing in the memory task used three measures: the *mean preparatory interval* from the end of the stimulus list to the beginning of the subject's response, the *mean word duration* measured from the beginning to the end of each word in the response and averaged across serial positions in the response, and *mean interword pause duration*, also calculated across serial positions. These measures were based on only those trials in which the response was entirely correct, and were averaged within a subject for trials of a particular type.

All subjects had usable data for span-length lists at all word lengths. However, not all subjects had usable data for subspan lists at all word lengths, because the initial length of testing (2 for the younger children and 3 for the older children) sometimes turned out to be the subject's maximal list length. In one additional case, a 4-year-old's data for lists one below span (i.e., span - 1) were not recorded on audiotape. Data for span - 1 length lists at all three word lengths were available for 8 of the younger children and 15 of the older children. The amount of data at a length of (span - 2) were insufficient for statistical analyses across word length.

Finally, the measure based on the speeded pronunciation task is termed the *maximal speech rate* (expressed in words/s), calculated as the mean time needed to pronounce a pair of words 10 times, divided by 20.

## RESULTS

The results begin with a replication of the ordinary relation between speech rate and memory span. Then, as the speech rates are examined in more detail and the timing of spoken recall is considered, limitations in the role of speech rate per se are indicated and other factors are highlighted.

### Memory Spans

Means for the maximal and cumulative memory span measures for each age group

and word length are reported in Table 1. Separate analyses of variance (ANOVAs) of maximal and cumulative memory span were conducted with age group as a between-subject factor and word length as a within-subject factor. The ANOVA of maximal span produced a main effect of age group,  $F(1,37) = 34.44$ ,  $MS_e = 1.13$ ,  $p < .001$ , and word length  $F(2,74) = 7.08$ ,  $MS_e = .32$ ,  $p < .002$ , but no interaction,  $F(2,74) = 1.38$ ,  $MS_e = .32$ ,  $p > .25$ . The ANOVA of cumulative span also produced main effects of age group,  $F(1,37) = 25.12$ ,  $MS_e = .91$ ,  $p < .001$ , and word length,  $F(2,74) = 26.04$ ,  $MS_e = .13$ ,  $p < .001$ ; these data replicate a previously observed pattern of results (e.g., Hulme & Tordoff, 1989). There also was an Age  $\times$  Word Length interaction,  $F(2,74) = 3.29$ ,  $MS_e = 0.13$ ,  $p < .05$ . As Table 1 indicates, its basis is that the word length effect was smaller for the younger subjects (see Table 1).

It should be noted that the presence or absence of an Age  $\times$  Word Length interaction is not an important distinction from our point of view. Any part of the word length effect that is based on covert rehearsal theoretically should increase with age, but the part of the word length effect based on overt pronunciation in spoken recall (which

TABLE 1  
AVERAGE MAXIMAL AND CUMULATIVE MEMORY SPANS OF EACH AGE GROUP AT EACH WORD LENGTH

Span measure	Word length		
	Short	Medium	Long
	Younger children ( $N = 16$ )		
Maximal	3.25 (.77)	2.88 (.81)	2.88 (.50)
Cumulative	2.80 (.72)	2.55 (.70)	2.42 (.51)
	Older children ( $N = 23$ )		
Maximal	4.43 (1.04)	4.26 (.69)	3.38 (.65)
Cumulative	3.90 (.73)	3.45 (.54)	3.11 (.50)

Note. Maximal and cumulative spans as defined in text. Standard deviations in parentheses.

could be the larger part of the effect) may be identical across ages.

### Maximal Speech Rates

The average maximal speech rates for all age groups and word lengths are presented in Table 2. As expected, an Age  $\times$  Word Length ANOVA of these rates produced large main effects of both age,  $F(1,37) = 62.50$ ,  $MS_e = .30$ ,  $p < .001$ , and word length,  $F(2,74) = 55.03$ ,  $MS_e = .06$ ,  $p < .001$ .

There also was an Age  $\times$  Word Length interaction,  $F(2,74) = 5.55$ ,  $MS_e = .06$ ,  $p < .006$ . As Table 2 makes clear, this interaction occurred because the effect of age was greater for the shorter words. It should be pointed out, however, that the older children spoke at a rate that was a little more than double the rate of the younger children for all three word lengths (ratios of 2.05, 2.40, and 2.15 to 1 for short, medium, and long words, respectively). A constant ratio of pronunciation rates across word lengths could have produced this interaction.

### Relation between Maximal Speech Rate and Memory Span Measures

Figure 1 plots the average cumulative memory span for each age group and word length as a function of the mean speech rate for the same age group and word length. The figure reveals a remarkably clean linear relation between the two, again replicating previous research (e.g., Hulme & Tordoff,

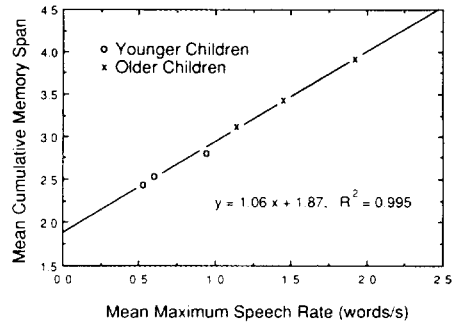


FIG. 1. Relation between average cumulative memory span and average speech rate for each age group and word length.

1989). As shown by the equation in the figure, the linear relation accounted for over 99% of the variance among the six cell means. Clearly, the data are not overly noisy.

In this light, it is interesting to observe what happens when one examines the relation between speech rate and memory span measures within each cell of the experimental design. These results are shown within Table 3, which contains correlations between all measures separately for each age group and word length. The younger group is shown below the diagonal in each panel, and the older group, above the diagonal. The fact that the speech rate/memory span correlations are less impressive than the linear relation shown in Fig. 1 is quite understandable on the basis of the restricted range of scores within each experimental cell. What is less predictable from the standard explanation of the word length effect (e.g., Baddeley, 1986) is that the correlations for the younger group are consistently *negative*; that is, among those subjects, faster speech rates for a particular word length correspond to poorer recall.

To examine this unexpected result more carefully, we averaged the results across word length separately for each subject. These individual-subject results are shown in Fig. 2, along with the regression line for each age group. As shown, the correlation between speech rate and memory span again was positive for the older group,  $r =$

TABLE 2  
AVERAGE MAXIMAL SPEECH RATES OF EACH AGE GROUP AT EACH WORD LENGTH

Age group	Word length		
	Short	Medium	Long
Younger children	.94 (.23)	.61 (.14)	.53 (.19)
Older children	1.93 (.63)	1.46 (.42)	1.14 (.27)

Note. Maximal speech rates from the separate speeded task, in words per second. Standard deviations in parentheses.

TABLE 3  
CORRELATIONS BETWEEN MEASURES FOR EACH COMBINATION OF AGE AND WORD LENGTH

	MS	CS	SR	Pr	WD	IP
Monosyllabic words						
Maximal span (MS)	—	.89*	.58*	-.05	.33	.27
Cumulative span (CS)	.90*	—	.63*	.05	.25	.07
Maximum speech rate (SR)	-.20	-.38	—	-.31	-.12	.03
Preparation interval (Pr)	-.28	-.44	.51*	—	.08	.08
Mean word duration (WD)	.24	.12	-.06	-.14	—	-.03
Mean interword pause (IP)	-.19	-.03	.13	.04	-.22	—
Bisyllabic words						
Maximal span (MS)	—	.65*	.39*	.04	-.05	.28
Cumulative span (CS)	.75*	—	.50*	-.07	-.17	.27
Maximum speech rate (SR)	-.67*	-.62*	—	-.34	-.31	.10
Preparation interval (Pr)	-.31	-.46	.75*	—	.27	-.53*
Mean word duration (WD)	-.20	-.24	-.06	-.21	—	.07
Mean interword pause (IP)	.34	.17	-.31	-.14	.09	—
Trisyllabic words						
Maximal span (MS)	—	.66*	.45*	-.18	.16	.37
Cumulative span (CS)	.74*	—	.47*	-.27	.18	.48*
Maximum speech rate (SR)	-.69*	-.41	—	-.39*	-.15	.04
Preparation interval (Pr)	-.60*	-.45	.31	—	.28	.13
Mean word duration (WD)	.08	-.01	-.07	-.07	—	.38
Mean interword pause (IP)	.04	-.10	-.13	-.43	-.30	—

Note. Younger group ( $n = 16$ ) is below the diagonal, older group ( $n = 23$ ) above. Significant correlations were those with  $r \geq .468$  for the younger group and  $r \geq .390$  for the older group.

\*  $p < .05$  or smaller, two-tailed test.

.44,  $p < .04$ , but negative for the younger group,  $r = -.59$ ,  $p < .02$ . With the age groups combined, the correlation in these data is strongly positive as expected,  $r = .79$ ,  $p < .001$ . It should be noted that the negative correlation in young children does not contradict previous data, because no previous study has examined the data in

this fine-grained manner. (Cowan, 1992 did not include speeded speech rates.)

Although the main focus of the study will be on the analyses of spoken recall and not on the relation between speeded speech rate and memory span as in most previous research, the analysis that we have presented does reinforce the important point that maximal speech rate is not the only major determinant of memory span. That possibility always did seem odd in light of the previous research suggesting that young children typically do not even use covert speech for mnemonic purposes (Flavell, Beach, & Chinsky, 1966; Henry, 1991b). Factors other than covert rehearsal, in particular the speed of other covert processes (Cowan, 1992) and lexical knowledge (Hulme, Maughan, & Brown, 1991) also have been shown to affect memory span and potentially could underlie the negative correlation in the younger group. Although any interpretation of this unexpected result

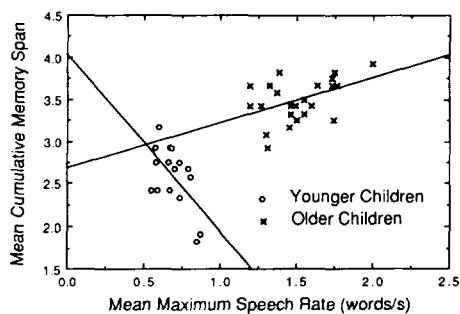


FIG. 2. Relation between cumulative memory span and maximal speech rate for each subject's data averaged across word lengths, and the best-fitting regression line for each age group.



can only be post hoc in nature, two possible interpretations will be offered below, after correlations between timing measures are reported.

### *Measures of the Timing of Spoken Responses*

**Preparatory intervals.** The mean preparatory interval in the response to span-length lists is shown in Table 4 for each combination of age and word length: An ANOVA of the preparatory interval with age group and word length as factors resulted in a main effect for age,  $F(1,37) = 12.16$ ,  $MS_e = .84$ ,  $p < .002$ . The mean preparatory interval was 1.76 s in the younger group and 1.16 s in the older group. No other effects approached significance.

In the studies of speeded list pronunciation conducted by Sternberg et al. (1978, 1980) increases in the preparatory interval with increasing list length were observed, presumably because more than just the first word was being prepared during that interval. That this interval decreases with age, despite an increase in the mean number of items in span-length lists, suggests that the speed or efficiency of at least one covert process increases with age.

Another ANOVA of the preparatory interval was conducted, with age group as a between-subject factor and word length (1, 2, or 3 syllables) and list length relative to span (i.e., span vs. span - 1) as within-subject factors, using just those subjects (8 younger and 15 older children) with all of

the necessary subspan data. This analysis produced a significant effect of relative list length,  $F(1,21) = 5.04$ ,  $MS_e = .26$ ,  $p < .04$ . The mean preparatory period was 1.24 s for span-length lists and 1.04 s for lists of length span - 1. No other effects involving list length as a factor were significant. (For the sake of simplicity, in the analyses that include list length as a factor, effects that do not involve list length will not be reported. Such effects are considered unimportant because they basically resemble effects obtained in the analyses without list length as a factor.)

If it is assumed that memory search occurs during the preparatory interval, the effect of list length on this interval could reflect the time needed to search for one additional item in the span-length lists than in span - 1 length lists, as Sternberg et al. (1978, 1980) proposed in their analysis of speeded list pronunciation. The absence of an effect of list length in a similar comparison in Cowan (1992) is puzzling, but perhaps can be attributed to the limitation of that study to one age group and monosyllabic words only.

**Word durations.** The mean response word duration in span-length lists, averaged across serial positions, is presented for each age group and word length in Table 5. An ANOVA of these data including age group and word length as factors yielded only a large main effect of word length,  $F(2,74) = 66.34$ ,  $MS_e = .01$ ,  $p < .001$ .

TABLE 4  
AVERAGE RESPONSE PREPARATORY INTERVAL (IN SECONDS) FOR EACH AGE GROUP IN SPAN-LENGTH LISTS OF EACH WORD LENGTH

Age group	Word length		
	Short	Medium	Long
Younger children	1.78 (.67)	2.00 (1.30)	1.48 (1.00)
Older children	1.30 (.64)	1.04 (.30)	1.13 (.56)

Note. Standard deviations in parentheses.

TABLE 5  
AVERAGE RESPONSE WORD DURATION (IN SECONDS) FOR EACH AGE GROUP IN SPAN-LENGTH LISTS OF EACH WORD LENGTH

Age group	Word length		
	Short	Medium	Long
Younger children	.47 (.13)	.58 (.10)	.74 (.11)
Older children	.56 (.09)	.62 (.08)	.75 (.14)

Note. Based on the mean across serial positions for each trial. Standard deviations in parentheses.

An Age Group  $\times$  Word Length  $\times$  List Length ANOVA of subjects who had complete data sets revealed a small but reliable main effect of list length,  $F(1,21) =$ ,  $MS_e = .003$ ,  $p < .02$ . The mean word duration was .64 s for span-length lists and .62 s for lists for length span - 1, a 20-ms difference. Given the extremely small magnitude of this effect, however, it will not be interpreted theoretically. No other effects involving list length approached significance.

*Interword pause durations.* The mean interword pause durations in the response to span-length lists, averaged across serial positions, are presented for each age group and word length in Table 6. Unlike the analysis of word durations, there was no effect of word length in the analysis of pause durations. No effect approached significance. This is theoretically consistent with the finding (Chase, 1977; Clifton & Tash, 1973) that word length has no effect on memory search rates.

In another ANOVA of interword pause durations, like the above but including also relative list length (span vs. span - 1) as a factor, a large and significant main effect of list length was obtained,  $F(1,21) = 6.55$ ;  $MS_e = .13$ ,  $p < .02$ . The mean pause duration was .38 s in span-length lists versus only .22 s in span - 1 length lists, a 160-ms difference. This large effect contrasts with the much smaller (20-ms) effect of list length on word durations. Thus, the results are basically consistent with the previous observation (Cowan, 1992; cf. Sternberg et

al., 1980) that list length affects primarily the pauses between spoken words in the response rather than the durations of words in the response.

*Comparisons across ages for equivalent list lengths.* Although older subjects had shorter preparatory intervals in span-length lists than did younger subjects, there was no age difference in word durations or interword pause durations in the responses. There were large effects of list length on interword pause durations, however. One interpretation of this result is that, during the interword pauses, subjects carry out covert processes at their own individual speeds, and that memory span is proportional to the speed of this processing. Assuming further that the amount of processing to be carried out in each pause is determined by the list length (as it would be if the process involved is a memory search), this would result in equal pause durations across age groups in span-length lists.

If processing speed is related to memory span, then the older children should respond faster than the younger children when tested on lists more comparable in length. In order to test this prediction objectively, we compared the response timing in the younger group on span-length lists ( $n = 16$ ) to older children on lists of length span - 1, using just those subjects in the older group with the necessary data at each word length ( $n = 15$ ). For the younger group, the mean list lengths were 3.25, 2.88, and 2.88 for short, medium, and long words, respectively, as shown in Table 1. For the older group, the mean lengths were 3.87 ( $SD = .92$ ), 3.53 ( $SD = .52$ ), and 3.13 ( $SD = .52$ ).

Even though the list lengths still were slightly longer in the older subjects, an Age  $\times$  Word Length ANOVA of the preparatory intervals indicated shorter intervals in the older ( $M = 1.02$  s) than in the younger ( $M = 1.76$  s) subjects,  $F(1,29) = 14.07$ ,  $MS_e = .89$ ,  $p < .001$ . Similarly, interword pauses were shorter in the older ( $M = .23$  s) than in the younger ( $M = .38$  s) subjects,  $F(1,29) = 7.98$ ,  $MS_e = .06$ ,  $p < .009$ . Nei-

TABLE 6  
AVERAGE RESPONSE INTERWORD PAUSE DURATION  
(IN SECONDS) FOR EACH AGE GROUP IN  
SPAN-LENGTH LISTS OF EACH WORD LENGTH

Age group	Word length		
	Short	Medium	Long
Younger children	.48 (.26)	.30 (.25)	.36 (.28)
Older children	.39 (.26)	.34 (.39)	.43 (.71)

*Note.* Based on the mean across serial positions for each trial. Standard deviations in parentheses.

ther of these analyses produced effects involving word length.

In contrast, in a similar ANOVA of word durations, there was only a large effect of word length,  $F(2,58) = 64.29$ ,  $MS_e = .006$ ,  $p < .001$ . The mean durations were .52 s (short words), .59 s (medium words), and .74 s (long words). No other effects were significant.

*Total response durations.* If there is a monotonic decay of memory for about 2 s across the response period, as suggested by Schweickert and Boruff (1986) and Stigler, Lee, and Stevenson (1986), then a subject's memory response should have to be completed within about 2 s. However, in the present data, the mean response times for span-length lists (the time from the end of the stimulus list to the end of the response) were much longer than 2 s, as shown in Table 7. There also was an effect of age on these response times,  $F(1,37) = 5.60$ ,  $MS_e = 3.59$ ,  $p < .03$ , reflecting longer response times in older subjects. No other effects were significant. These effects could indicate that faster covert processing in older subjects results in faster reactivation of memory and therefore allows these subjects to speak for a longer total duration without losing the needed information from phonological short-term memory.

#### *Relations between Speech Timing and Other Measures*

Within each combination of age and word length, the mean preparatory interval,

TABLE 7  
MEAN RESPONSE TIMES (IN SECONDS) FOR  
SPAN-LENGTH LISTS AT EACH AGE AND  
WORD LENGTH

Age group	Word length		
	Short	Medium	Long
Younger children	4.38	4.27	4.29
Older children	5.22	4.84	5.41

*Note.* Correctly repeated lists at maximal span were used. Response times were calculated as the mean period from the end of the stimulus list to the end of the spoken response.

mean word duration, and mean interword pause duration of span-length lists were correlated with maximal speech rate and memory span measures. These correlations are presented, along with those between maximal speech rate and span, in Table 3.

The measures of different aspects of timing within an age and word length were not consistently related to memory span or to each other; they appear to index basically independent aspects of responding. However, there was one set of relatively orderly correlations that may provide clues to why the relation between maximal speech rate and memory span was unexpectedly negative within younger children, but positive, as expected, within older children (see above). Specifically, the relation between maximal speech rate and the preparatory interval was a positive one in the younger children, at all three word lengths (short,  $r = .51$ ,  $p < .04$ ; medium,  $r = .75$ ,  $p < .001$ ; long,  $r = .31$ , n.s.), whereas this correlation was negative in the older children at all three word lengths (short,  $r = -.31$ , n.s.; medium,  $r = -.34$ , n.s.; long,  $r = -.39$ ,  $p < .05$ ). This pattern means that, among the younger children, the ones who spoke at a faster rate in the speeded task nevertheless took longer on the average to prepare their span-length responses than did the ones who spoke at a slower rate in the speeded task, without any apparent benefit of this added preparation time. In contrast, the older children who could speak more quickly also prepared their span-length responses more quickly and recalled more.

These age differences in the pattern of individual results are intriguing and warrant further study. One possible interpretation is that the young children who can speak more quickly also are just beginning to be able to use certain retrieval strategies but do so inefficiently, hurting their memory performance in the process, whereas older children might use such strategies beneficially. It is well known that children's performance on a task can decline temporarily when a new strategy is first tried (Strauss & Stavy, 1982). However, a second possible

interpretation is that the subjects with a better memory span are slowed in pronunciation because their phonological representations are more detailed than those of the less advanced children. It is clear that a better memory representation of words would assist memory span in a manner that is independent of speech rate (Hulme et al., 1991).

#### DISCUSSION

The present study helps to clarify the nature of the well-known linear relation between maximal speech rate and memory span. Although this relation has been obtained no matter whether the variance in speech rate was based on stimulus factors or subject factors (Baddeley et al., 1975; Case et al., 1982; Cowan et al., 1992; Hulme et al., 1984; Naveh-Benjamin & Ayres, 1986; Nicolson, 1981; Schweickert & Boruff, 1986; Standing et al., 1980; Zhang & Simon, 1985), the present results indicate that the effects of word length and age during childhood on the timing of spoken recall differ from one another.

Word length (i.e., the number of syllables in each stimulus word) affected the duration of words in the spoken response, but not the duration of silent periods in the response. In contrast, age affected the duration of the preparatory interval and interword pauses in the response, but not the duration of spoken words in the response. The effect of age on interword pauses was observed when the two age groups were compared on lists of about the same length, whereas the effect of age on the preparatory interval was observed not only in that comparison, but also in an age comparison using the longest list successfully repeated by each subject.

These results have important implications for theories of memory span. A great deal of prior work summarized by Baddeley (1986) implicates time as a constraint in short-term verbal memory span, but an unproven simplifying assumption has been that the time constraint operates in the

same way no matter how speech rate is varied. Baddeley suggested that subjects can recall as much of a particular type of material as they can pronounce in about 2 s because there is a phonological memory store from which any particular item decays in about 2 s unless it is articulated again before that time limit. Thus, an "articulatory loop" presumably repeats the list in cycles of about 2 s.

Within the general framework of Baddeley's proposed system, though, there could be separate contributions of the speed of covert rehearsal and overt pronunciation. The latter contribution could occur because the phonological memory of some items is lost while other items are pronounced. The finding by Cowan et al. (1992) that word length effects occurred primarily because of the lengths of words to be repeated first suggests that much of the effect of word length in fact is based on overt pronunciation. This conclusion was supported also by Henry (1991a), who, as noted above, found that the effect of word length in 5-year-olds was abolished when a pointing response was used instead of a verbal response.

Given that word length affected the duration of words in the response within the present study, its influence on recall may have been due to an effect on the amount of phonological information that was lost while a subject was busy speaking. In contrast, because age differences instead affected the duration of silent periods in the response, its influence on recall may have been due to an effect on the nature or speed of covert mnemonic processes taking place during those silent periods.

An important unknown is the nature of those covert mnemonic processes and their development. Although the present data cannot answer that difficult question, it can provide clues when considered in combination with previous research. One possibility is that some subjects engage in covert verbal rehearsal during the silent periods. However, as Cowan (1992) discussed in detail, there was far too little time either in the

preparatory interval or between words in the response for subjects to have rehearsed the entire list between spoken words; rehearsal has been shown to take place at a rate no faster than the maximal speech rate (Landauer, 1962), whereas memory search is much faster (Sternberg, 1966; Sternberg et al., 1978, 1980). Therefore, it seems unlikely that rehearsal could serve the function of a covert search through the list to identify the item in memory to be spoken next. Previous studies also have suggested that memory search does not involve covert rehearsal, because the word length effects that are caused by rehearsal (e.g., Baddeley et al., 1975) are not obtained in search tasks (Clifton & Tash, 1973), even when it is sequential information that is being searched for (Chase, 1977).

Sternberg et al. (1978, 1980) summarized a large number of experiments aimed at determining the nature of memory search in a procedure in which subjects were to repeat short lists of words as quickly as possible. One of the prominent findings (Sternberg et al., 1980) was that the periods between words in the response increased with increasing list length. That finding was replicated in the present study. In particular, responses to lists of length (span - 1) included significantly shorter preparatory intervals and interword pauses than responses to lists of span length. There was not enough data for lists of length (span - 2) to determine if the silent intervals were shorter still, as would be expected on the basis of Sternberg et al. (1980), but Cowan (1992) studied a larger sample of 4-year-olds and found exactly that.

Thus, whatever memory search processes take place in the procedure of Sternberg et al. (1978, 1980), which involved only subspan lists and speeded responses, may well take place in ordinary spoken recall as well. It may be either a serial search process as Sternberg et al. have proposed, or a parallel, capacity-limited search process as Ratcliff (1978) has suggested.

According to the theories of either Stern-

berg or Ratcliff, subjects would have to search through the entire list repeatedly in order to determine the item to be spoken next in the response. If we can assume this to be the case, then the present finding that word length did not affect the duration of silent intervals in the response is consistent with the notion that a memory search process other than covert rehearsal was carried out during those silent intervals.

The present data are inconsistent with the hypothesis (Schweickert & Boruff, 1986; Stigler et al., 1986), based on a simple interpretation of the articulatory loop theory, that memory decays steadily for about 2 s during the response period (which would be one way to account for the finding that subjects can recall about as much as they can pronounce in about 2 s). Responses to span-length lists lasted about 4.3 s beyond the stimulus list in younger children and about 5.2 s in older children. One alternative hypothesis, suggested by Cowan (1992), is that the memory search processes that occur during the silent periods in recall serve to reactivate some of the items in phonological memory. The age difference in the mean duration of span-length responses, as well as the shorter silent periods within the responses of the older children, might suggest that older children carry out certain covert processes more quickly than younger children do. This suggestion receives support from the finding (Keating, Keniston, Manis, & Bobbitt, 1980) that memory search is faster in older children. This does not necessarily indicate that the search processes are identical in form at the two ages, but simply that the older children accomplish the search task faster, however it actually is accomplished.

It should be noted that the effects of age on timing within the memory response differ from those of a task in which 8- and 10-year-old children were to pronounce triads of words as quickly as possible (Hulme et al., 1984). In those speeded responses, the older children articulated the individual words more quickly than the younger chil-

dren, with no significant difference in the periods between words. This finding is, however, theoretically consistent with the present account. The maximal pronunciation rate is expected to be faster in older children, even though there is no evidence of an effect of age on the rates of pronunciation within the memory response, which is unsped. The reason that an age effect on the interword pauses in the speeded responses was absent may have been that the triads imposed little memory load and thus required few memory search steps at either age.

There are two overriding questions that still have not been addressed. The first is why the close correlation between maximal speech rate and memory span occurs. The hypothesis that it occurs because memory span is critically dependent on the rate of covert rehearsal during a 2-s rehearsal cycle (Baddeley, 1986) remains theoretically possible, but is weakened by the finding of other correlates of recall in the timing of responses. In any case, given that covert rehearsal takes about as long as the maximal rate of overt pronunciation (Landauer, 1962), it is not clear when during the reception of the stimulus list such a long cycle could operate. The implication would have to be that rehearsal of early list items occurs concurrently with the perception of subsequent items in the list. Such a rehearsal process would require split attention (Guttentag, 1984), and it is difficult to believe that young children could do it, especially in light of other evidence suggesting that they do not rehearse at all (Flavell et al., 1966; Henry, 1991b). An alternative possibility is that the connection between maximal speech rate and memory span is not directly causal, and that the main causal variable instead is the memory search rate.

Perhaps the most fundamental constant in memory span actually is the maximal permissible duration of the silent interval between items in the response. It may be that phonological memory decays during this interval, and that the time available to

search memory for an item is limited accordingly. This account is analogous to that of Baddeley (1986), but with two big differences. First, it is based on a cycle (of memory search) that is closer to 300–500 ms (the duration of an interword pause) than to 2 s. Second, one variant of the account permits that the memory search process might take place on more than one item concurrently, in a capacity-limited parallel, rather than a serial, manner (e.g., Ratcliff, 1978).

A still-remaining question for this account would be why the 2-s limit in memory span occurs. This limit could occur because there is a relatively fixed ratio between the time it takes a subject to conduct a memory search and the minimal time it would take the same subject to pronounce the list (e.g., 350 ms to 2 s). This type of fixed ratio is made plausible by the finding of a general speed factor that distinguishes among individuals of different developmental levels and capabilities consistently across a wide range of information processing tasks (Hale, 1990; Kail, 1988; Salthouse, 1985).

Notice that the account based on memory search instead of covert rehearsal questions the support for a phonological memory store lasting about 2 s. That should be viewed as a benefit of the account, inasmuch as a large amount of research with other procedures instead points toward the existence of two types of short-term store, one lasting several hundred milliseconds and one lasting 10–20 s (Cowan, 1984, 1988; Cowan, Lichty, & Grove, 1990). Speaking conservatively, it at least seems premature to draw an inference about the exact duration of the transient phonological store that is used in memory span tasks.

The proposition that processing speed determines memory span receives tentative quantitative support from the present data. Let  $S_y$  and  $S_o$  be the maximal memory spans of the younger and older subjects, respectively, let  $L_y$  and  $L_o$  be the lengths of lists that they repeat correctly, and let  $P_y$  and  $P_o$  be their mean interword pauses in the responses to those lists. If we make the

simplifying assumption that the interword pause is used to process each list item for an equal amount of time, then the processing rates in the two groups during the pause is  $L_y/P_y$  and  $L_o/P_o$ . If the memory span is proportional to the processing rate, then we should find that  $S_y/S_o = (L_y/P_y)/(L_o/P_o)$ . Averaged across word lengths, the ratio of mean spans ( $S_y/S_o$ ) for all subjects was .72 and the ratio of mean processing rates on span-length lists was a nearly identical .75, in close agreement with the model. In a comparison of the younger group's span-length performance with the older children's performance on lists of length span - 1 (considering only the 15 subjects with a complete data set), the ratio of mean spans was 0.67 and the ratio of mean processing rates was 0.53. The fact that the speed model fits better when used exclusively on span-length lists may suggest that the rate of processing slows down when span is reached, presumably because of the contribution of something like central executive processes (Baddeley, 1986) or a focus of attention (Cowan, 1988). In future research, a separate memory search task such as the one used by Keating et al. (1980) should be used as an independent measure of processing rate, as according to this account it should correlate well with memory span.

It still is uncertain exactly which processes play a causal role in individual differences in memory span. It might not be any one process, but a combination of several mnemonically relevant processes (e.g., word identification, memory search, response planning, and/or covert rehearsal) that are accomplished more quickly in subjects with higher spans. In terms of correlational evidence, one would no longer be compelled to choose between proposals that memory span is correlated with the maximal speech rate (Baddeley et al., 1975), versus with memory search (Cavanagh, 1972), or the time it takes to identify words (Case, Kurland, & Goldberg, 1982; Hitch, Halliday, & Littler, 1989).

On the other hand, the various speed variables may not be everywhere interchangeable. Hitch et al. (1989) examined written memory span in children 8–11 years old and found that pronunciation rates provided a close linear fit to memory span, whereas identification times did not fit as well. However, when articulatory suppression was used, identification times provided the better fit to the data. The time-dependent processes that enter into memory span may include some obligatory ones (e.g., word identification and memory search) and some optional processes that occur only in some subjects (e.g., covert rehearsal only in children about 7 years and older).

Finally, a subsidiary finding of the present study was that, although the correlation between the maximal speech rate and memory span observed across conditions in previous studies clearly was replicated here (Fig. 1), a finer-grained analysis indicated that some temporal factors operate outside of this linear relation. Specifically, the relation between maximal speech rate and memory span within the younger, 4-year-old group of children was negative (Fig. 2). There may be some factor (e.g., the completeness of phonological representation) that contributes to slower maximal speech among 4-year-olds while increasing span for non-temporal reasons (e.g., Hulme et al., 1991). It appears that what is needed now is a detailed analysis of mnemonic processes that occur at various points during recall in the memory span task and of the efficiency of potential component skills separately.

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